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Use of Marker Bands for Determination of Fatigue Crack Growth Rates and Crack Front Shapes in Pre-Corroded Coupons

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Introduction

Visual monitoring of propagating fatigue cracks is not practical for monitoring fatigue crack growth in corroded specimens. Even the slightest corrosion will typically obscure an advancing fatigue crack so that crack length measurements cannot be performed. This problem is greatly magnified for small crack lengths (a < 0.25mm [0.01"]) because typical remote crack measurement techniques such as Electric Potential Difference (EPD) and compliance lack the sensitivity required to accurately measure small cracks. EPD and compliance are also averaging techniques so fatigue crack shapes and crack lengths cannot be determined in the early stages of testing especially when the cross section of the specimen is non-symmetric. Determination of crack length vs. cycle count (a vs. N) and fatigue crack front history after testing can be achieved by the selective marking of the fatigue surface with coded marker bands generated by applying a series of fatigue underloads at predetermined intervals. Marker bands are groups of microscopic striations that when generated in the proper fashion are readily identifiable by optical and scanning electron microscopy (SEM). The objective of this study was to develop a technique that will allow determination of a vs. N, fatigue crack growth rate and crack front shapes in test coupons at small crack lengths, as close as possible to the point of crack initiation. Two similar techniques using marker bands are demonstrated here. Both employ SEM and may be used similarly with optical microscopy.

Procedure

Single edge notched tension specimens were used for the purpose of this study. The notch consisted of a 100° countersink with a 0.13mm-0.25mm (0.005”-0.010”) shank (Fig. 1). Specimen 1, machined from an ALCLAD 2024 aluminum sheet, was gripped with a pair of 5 bolt clevis while Specimen #2, machined from a 2024 aluminum sheet without cladding, was gripped with hydraulic grips. Both methods gripped 3 inches of the specimen on each side leaving a 6 inch gauge length. The surface of specimen #1 was polished before testing but specimen #2 was tested in the as-machined condition. Prior to fatigue testing, two inches in the center of specimen #2 was submersed in a 3.0 wt.% NaCl solution for 5 days which caused extensive pitting and covered the surface with corrosion products in the exposed region. To prevent corrosion and crack initiation in non-preferred areas, primarily the countersink region, one side of the specimen was masked as shown in Figure 2 with marine epoxy to prevent exposure to the corrosive environment during the specimen preparation process.

Specimen #1 was tested under constant amplitude loading conditions with maximum load (P_{max})=2900 lb and stress ratio (R)=0.1. Specimen #2 was tested under constant amplitude loading conditions with P_{max}=2040 lb and R=0.1 (Table 1). After every 2000 growth cycles in both specimens, a series of coded marker block loading sequences was used to mark the fatigue surfaces. The loading sequences consisted of 100 underloads (75% of P_{max}) combined with 10 cycles at P_{max} alternated a given number of times. This process was designed to mark the fatigue surfaces with recognizable patterns that could later be identified by optical and scanning electron microscopy. Marker blocks that created 3 unique marker band patterns were continuously rotated in sequence between growth cycles to mark the surface with a repeatable pattern (Fig. 3). With three distinct marker bands repeated in the same order it became much less probable that a given set of marker bands would be missed because the sequence could be followed during the search process. Both tests were stopped before the cracks grew fully out of the countersink.

The specimens were analyzed in a Cambridge 240 Stereoscan SEM with analog readouts on the X and Y specimen stage controllers. The specimen translation stage with analog readouts was used to assign X-Y coordinates to Specimen #1 for each marker band location found. Precautions were taken to reduce backlash in the mechanical gears driving the specimen stage. The X-Y coordinates were plotted so that crack length measurements could be made. Crack length measurements were made along the geometric center of the specimen. Crack growth rates and crack front shapes were determined from the measurements taken from the plot of the X-Y coordinates.

A less efficient but equally effective technique was employed for Specimen #2. A montage of the entire fatigue surface of Specimen #2 was constructed at a magnification of 149X. After the construction of the montage, higher magnifications up to 10,000X were used to search for and locate the marker bands. Marker band locations were then recorded directly onto the fatigue surface montage. Finally crack length measurements were made along the center of the montage so that crack growth data and crack front shapes could be determined. Average crack length measurements were made along the geometric center of the specimen. This method of recording marker band locations is especially time consuming due to the construction of the cumbersome montage but it is an extremely useful technique when the spacing between marker bands is small or if the SEM being used lacks a digital or analog readout for the specimen translation stage.

The SEM was used exclusively for marker band analysis in this study but optical microscopy could be used if the microscope were equipped an X-Y translation stage. A long focal length objective lens with good depth of field characteristics that yields a total magnification of between 350X and 550X is also recommended.

Results

The plot of the X-Y coordinates and fatigue crack fronts at 2000 cycle intervals taken from specimen #1 are shown in Fig. 4. Fig. 4a shows marker band sets 1 through 10 that were created during the initial stages of testing. The intervals between the marker bands are clearly defined and crack front shapes can be easily discerned with the help of lines used to connect the regions where marker bands could be found. Marker bands in this region of the specimen appeared incongruent when viewed in Fig. 4b but crack front shapes and marker band intervals were clearly visible when viewed on this scale.

Similarly, marker band data for sets 10 through 21, from the early stages of crack growth, and crack front lines are shown in Fig. 4b. A total of 21 sets of marker bands were found in specimen #1. Only one marker band data point could be located for marker bands #1 and #2. The crack growth data obtained from Specimen #1 can be found in Table 2 and the a vs. N plot is shown in Fig. 5. The smallest crack front found in this specimen was 100μm (0.004"). The X-Y coordinates obtained from Specimen #1 marker bands were catalogued in Appendix 1.

The fatigue surface micrograph montages that were constructed from specimen #2 are shown in Figures 6a and 6b. A total of 25 sets of marker bands were found. Fig. 6a shows marker bands #1-8 near the initiation site of specimen #1. All marker bands are labeled and the entire fatigue surface is shown in Fig 6b. All measurements were taken from the montage in Fig. 6a and Figure 6b is only used to highlight the crack front shapes closest to the initiation site. The short black and white lines indicate the location and orientation of marker bands found with the SEM. The white lines illustrate the fatigue crack fronts at intervals of 2000 cycles by filling in between the marker bands that were found. A clear crack front was drawn by connecting the dashed lines in regions that contain the best information. Enough data to draw complete lines representing 100% of a given crack front can not always immediately be found on the fatigue surface because fatigue striations preferentially mark some crystallographic orientations. Marker band data in specimens of this nature typically consist of regions along the crack front that are clearly marked combined with regions where little if any marker band information exists. This requires that only a reasonable amount of information, not thousands of data pairs, be obtained to fully reconstruct the history of small crack growth in a pre-corroded countersink edge notch specimen. The final crack front is visible in Fig 6a. The a vs. N and fatigue crack growth rates obtained from the Specimen #2 marker band data can be seen in Table 3 and the a vs. N plot for specimen #1 is shown in Fig. 7.

Summary

The fatigue crack growth history (a vs. N, fatigue crack growth rate and crack front shape) of a countersink edge notch specimen can be determined from sets of marker bands generated on a fatigue surface during the early stages of testing of fatigue coupons. Marker bands are routinely found at crack lengths of less than 200 μm (0.008") proving that the fatigue crack growth history for small cracks can be consistently reconstructed for all but the smallest fatigue cracks ($a < 100\mu m$ [0.004”]).

This technique is also useful for specimens with unusual geometry where optical measurements for crack growth cannot be taken whether the specimen is corroded or not, especially in the region where small crack growth occurs. One limitation, however is that the marker bands will become wider and more diffuse as crack growth rates increase. This makes the marker bands more difficult to see with SEM or optical microscopy.

Table 1
Experimental Conditions

	Specimen #1	**Specimen #2**
P_{max}	2900 lb	2040 lb
Marking load	0.75 P_{max}	0.75 P_{max}
Corrosion history	None	5 days in 3.0% NaCl solution
Material	ALCLAD 2024 T-3	2024 T-3
Grips	5 pin	Hydraulic

Table 2
Fatigue Crack Growth Rate Data
For Specimen #1

Crack Length (mm)	**Cycles (X1000)**	**Δa (mm)**	**da/dN (mm/cycle)**
0.100	108		
0.120	110	0.020	1.00e-05
0.145	112	0.025	1.25e-05
0.176	114	0.031	1.55e-05
0.198	116	0.022	1.10e-05
0.228	118	0.030	1.50e-05
0.260	120	0.032	1.60e-05
0.314	122	0.054	2.70e-05
0.340	124	0.026	1.30e-05
0.396	126	0.056	2.80e-05
0.488	128	0.090	4.50e-05
0.563	130	0.075	3.75e-05
0.632	132	0.069	3.45e-05
0.735	134	0.103	5.15e-05
0.855	136	0.120	6.00e-05
0.994	138	0.139	6.95e-05
1.170	140	0.176	8.80e-05
1.396	142	0.226	1.13e-04
1.670	144	0.274	1.37e-04
1.958	146	0.288	1.44e-04
2.340	148	0.382	1.91e-04

Table 3
Fatigue Crack Growth Rate Data
For Specimen #2

Crack Length (mm)	Cycles (X1000)	Δa (mm)	da/dN (mm/cycle)
0.179	42		
0.187	44	0.008	4.00e-06
0.204	46	0.017	8.50e-06
0.220	48	0.016	8.00e-06
0.237	50	0.017	8.50e-06
0.260	52	0.023	1.15e-05
0.300	54	0.040	2.00e-05
0.337	56	0.037	1.85e-05
0.371	58	0.034	1.70e-05
0.439	60	0.068	3.40e-05
0.528	62	0.089	4.45e-05
0.596	64	0.068	3.40e-05
0.669	66	0.073	3.65e-05
0.800	68	0.131	6.55e-05
0.953	70	0.153	7.65e-05
1.098	72	0.145	7.25e-05
1.246	74	0.148	7.40e-05
1.438	76	0.192	9.60e-05
1.660	78	0.222	1.11e-04
1.855	80	0.195	9.75e-05
2.128	82	0.273	1.37e-04
2.417	84	0.289	1.45e-04
2.741	86	0.324	1.62e-04
3.115	88	0.374	1.87e-04
3.583	90	0.468	2.34e-04

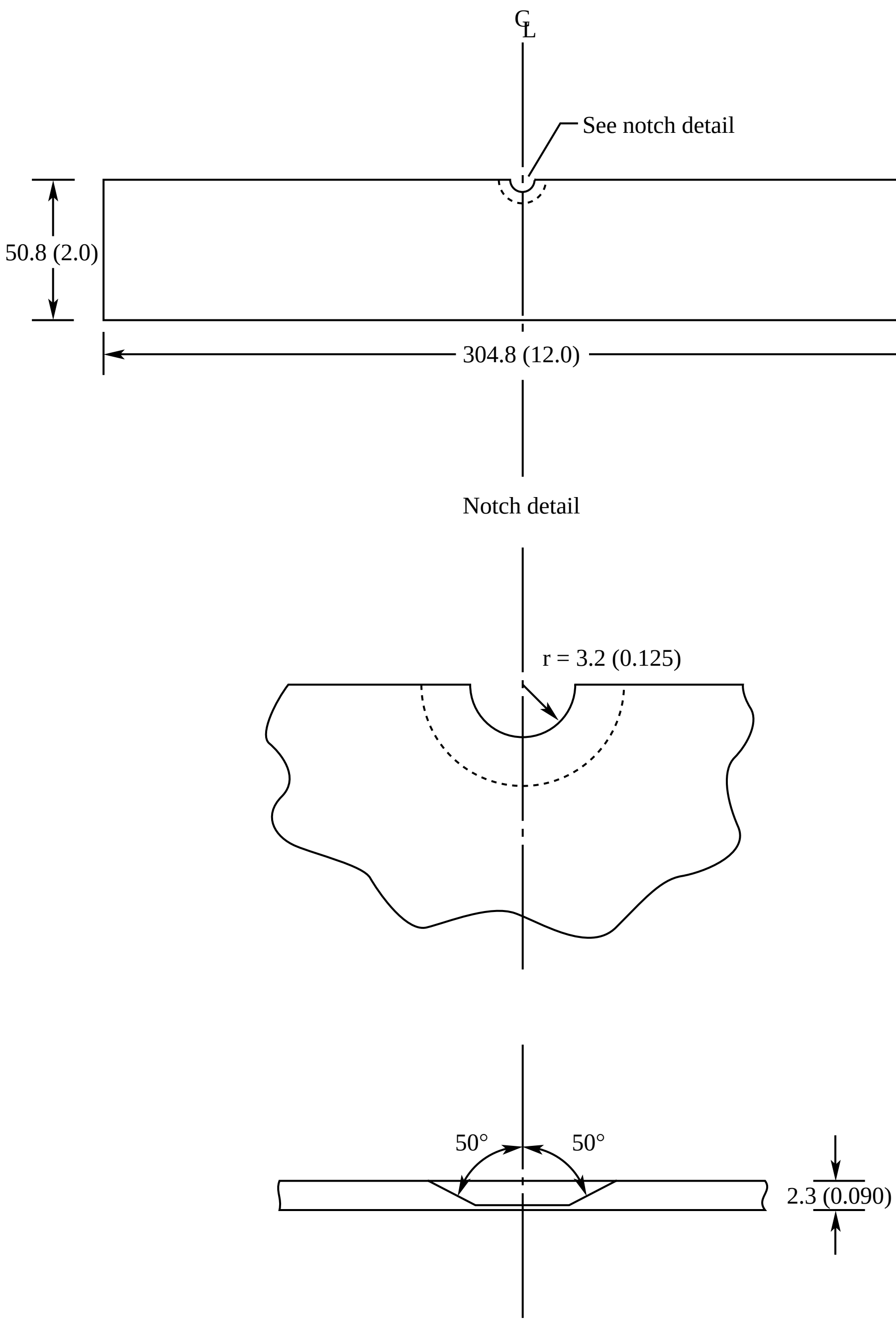


Figure 1 Schematic showing the countersink single edge notch tension specimen. Measurements are given in mm and (inches).

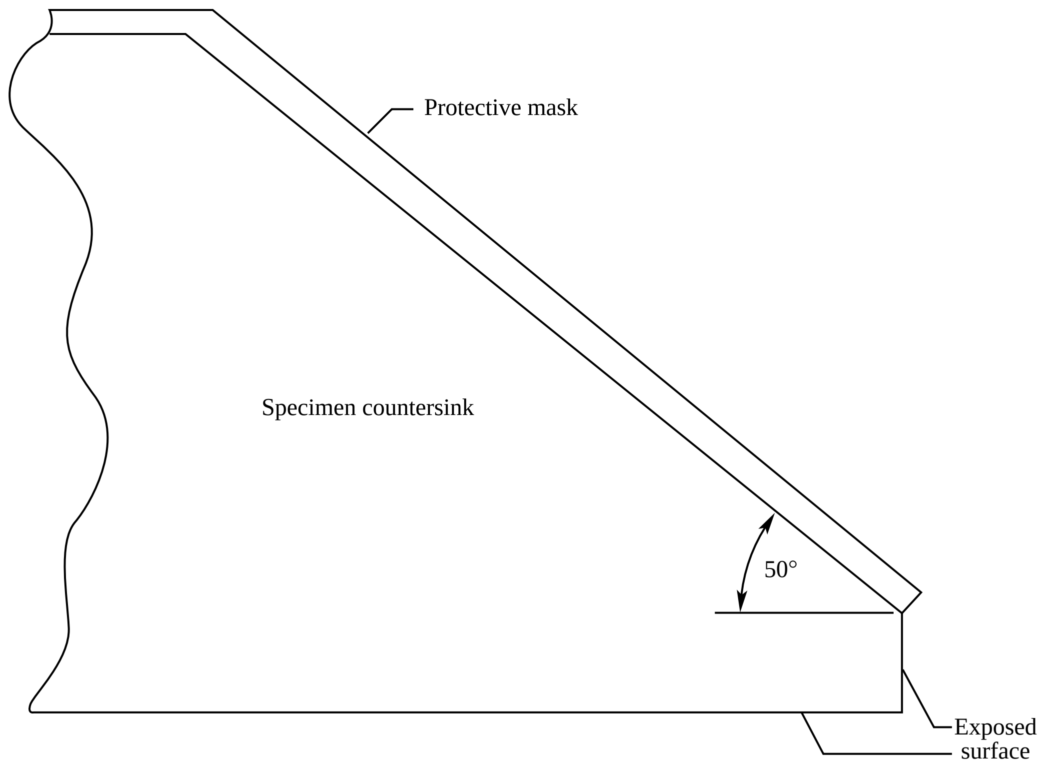


Figure 2 Schematic detailing the coverage of the test specimen with marine epoxy.

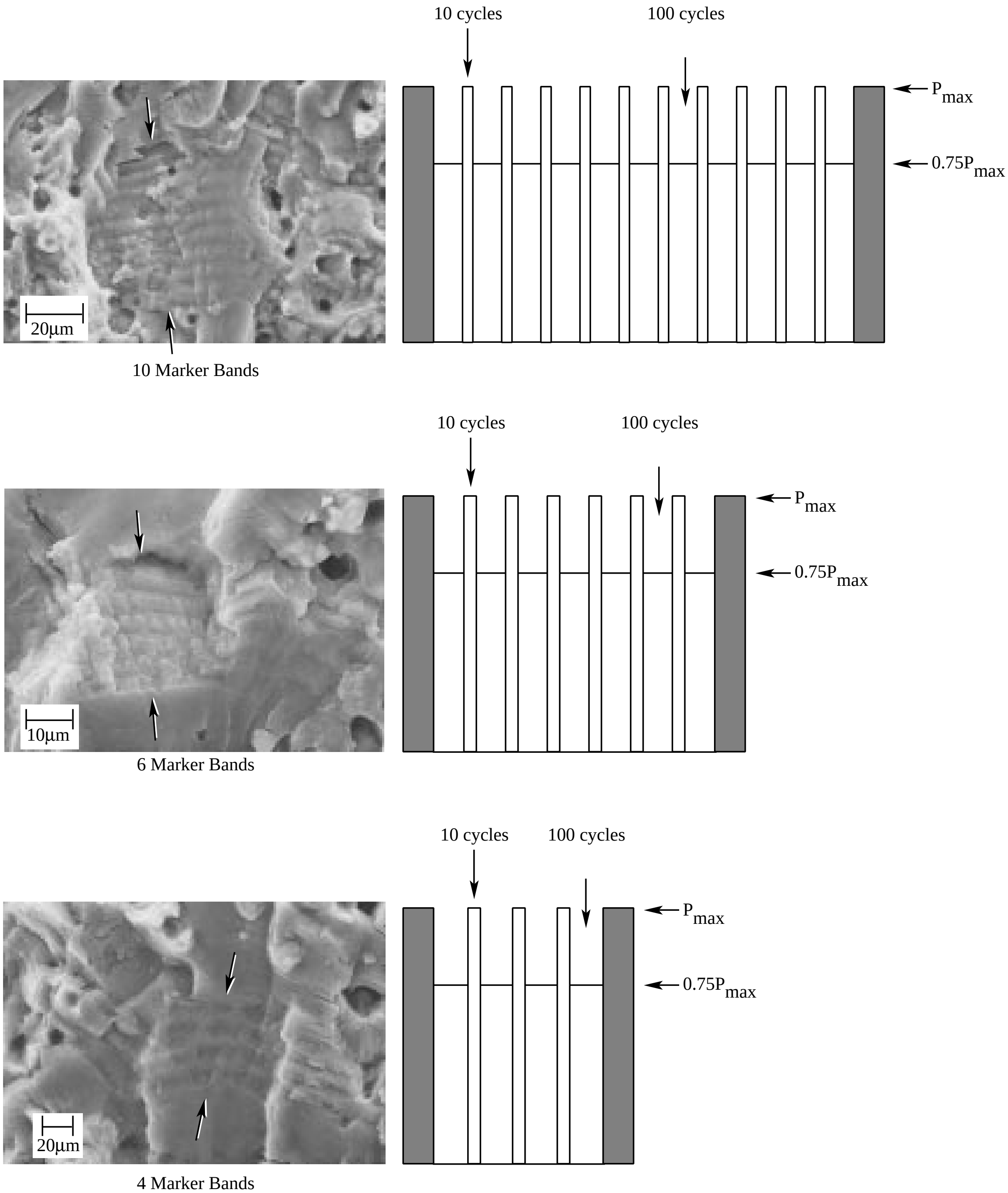
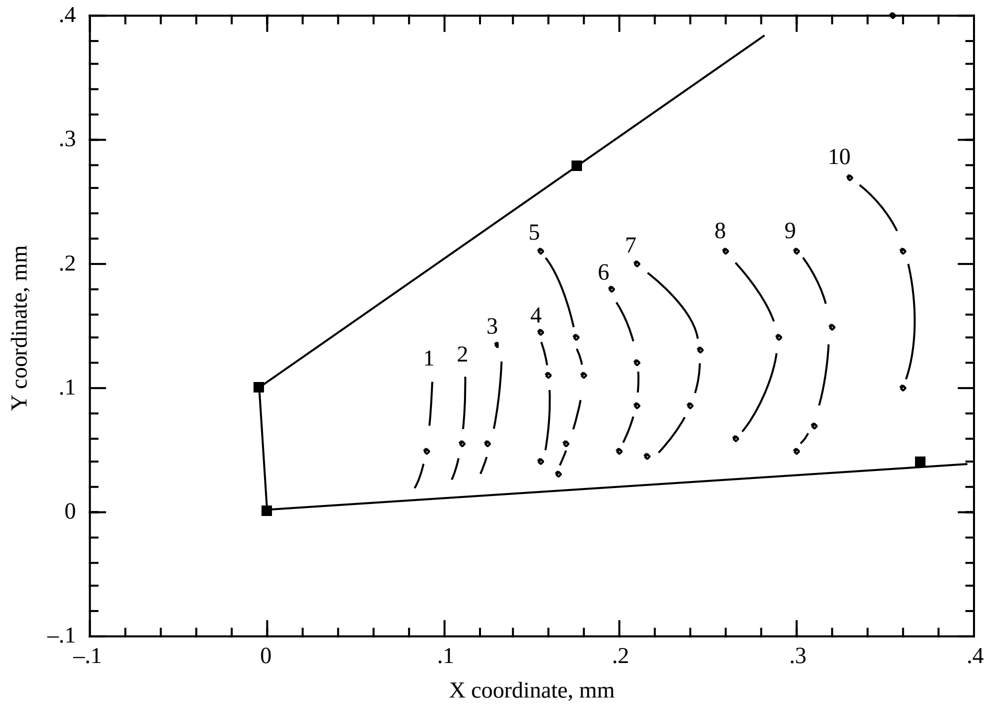
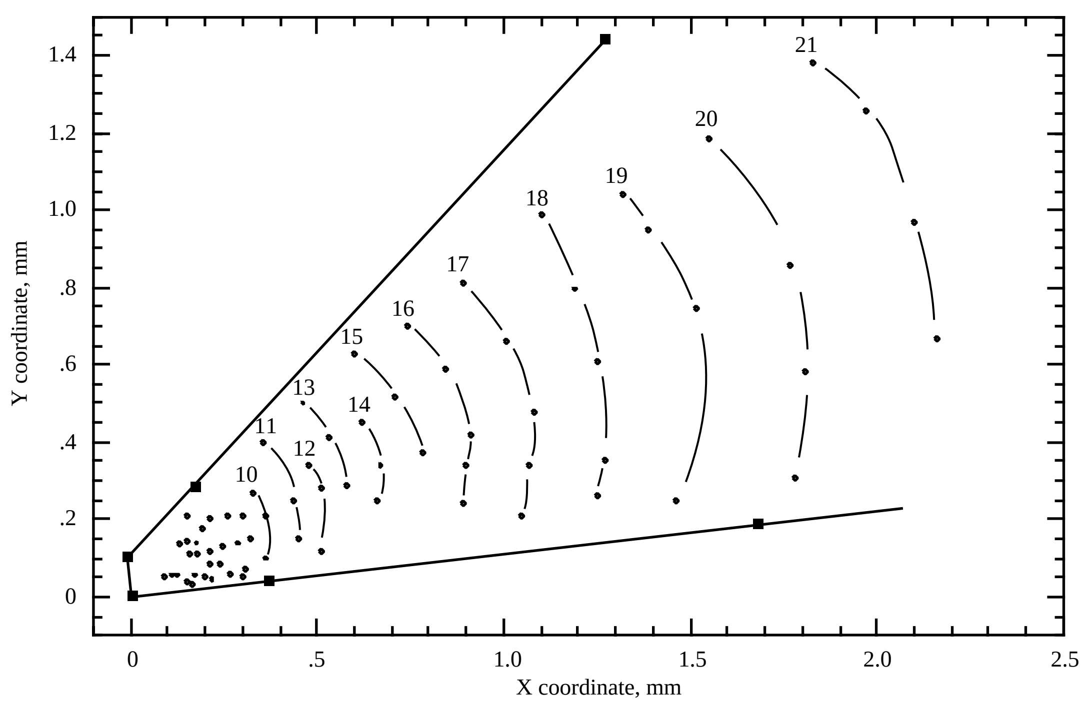


Figure 3 SEM micrographs paired with marker block loading sequences for a) 10 marker bands, b) 6 marker bands, and c) 4 marker bands. Wider blocks represent 100 marking cycles and narrow blocks represent 10 cycles at P_{max}. Shaded blocks represent 2000 growth cycles. Arrows on the micrographs mark the beginning and end of the marker bands.



(a)



(b)

Figure 4 Specimen #1 marker band plot and crack fronts for a) marker bands 1-10 and b) marker bands 10-21. The solid connected lines represent the outline of the countersink region of the specimen.

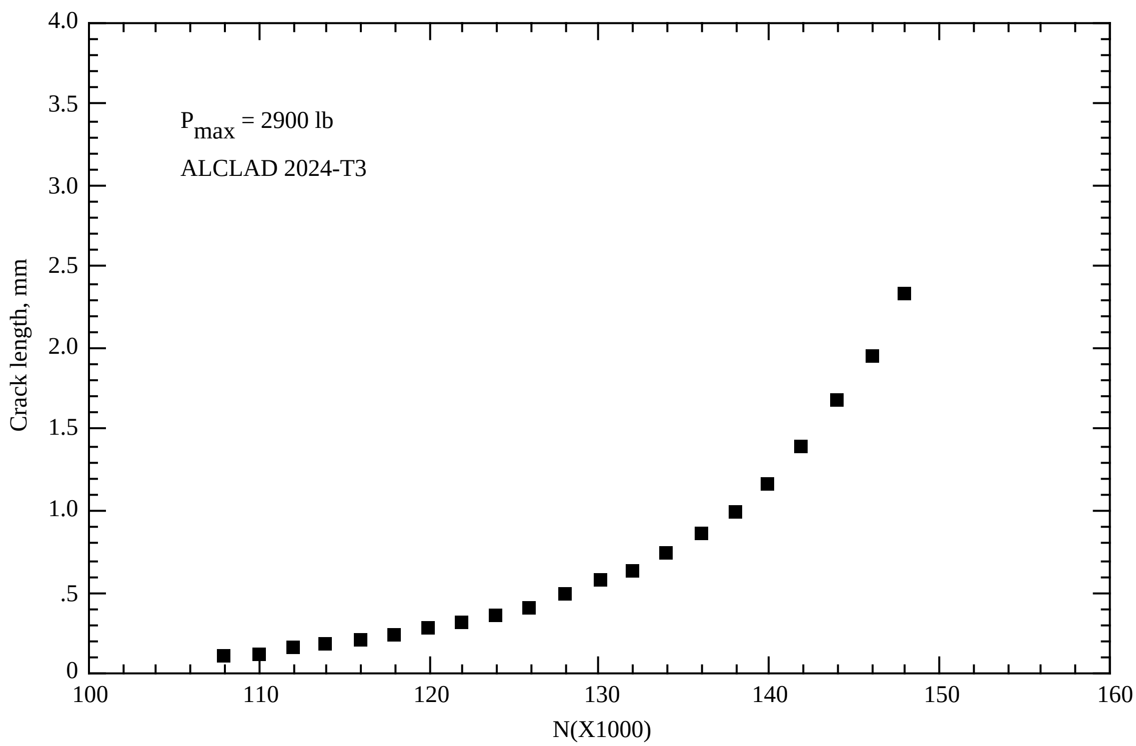


Figure 5 Fatigue crack length vs. cycle count for Specimen #1.

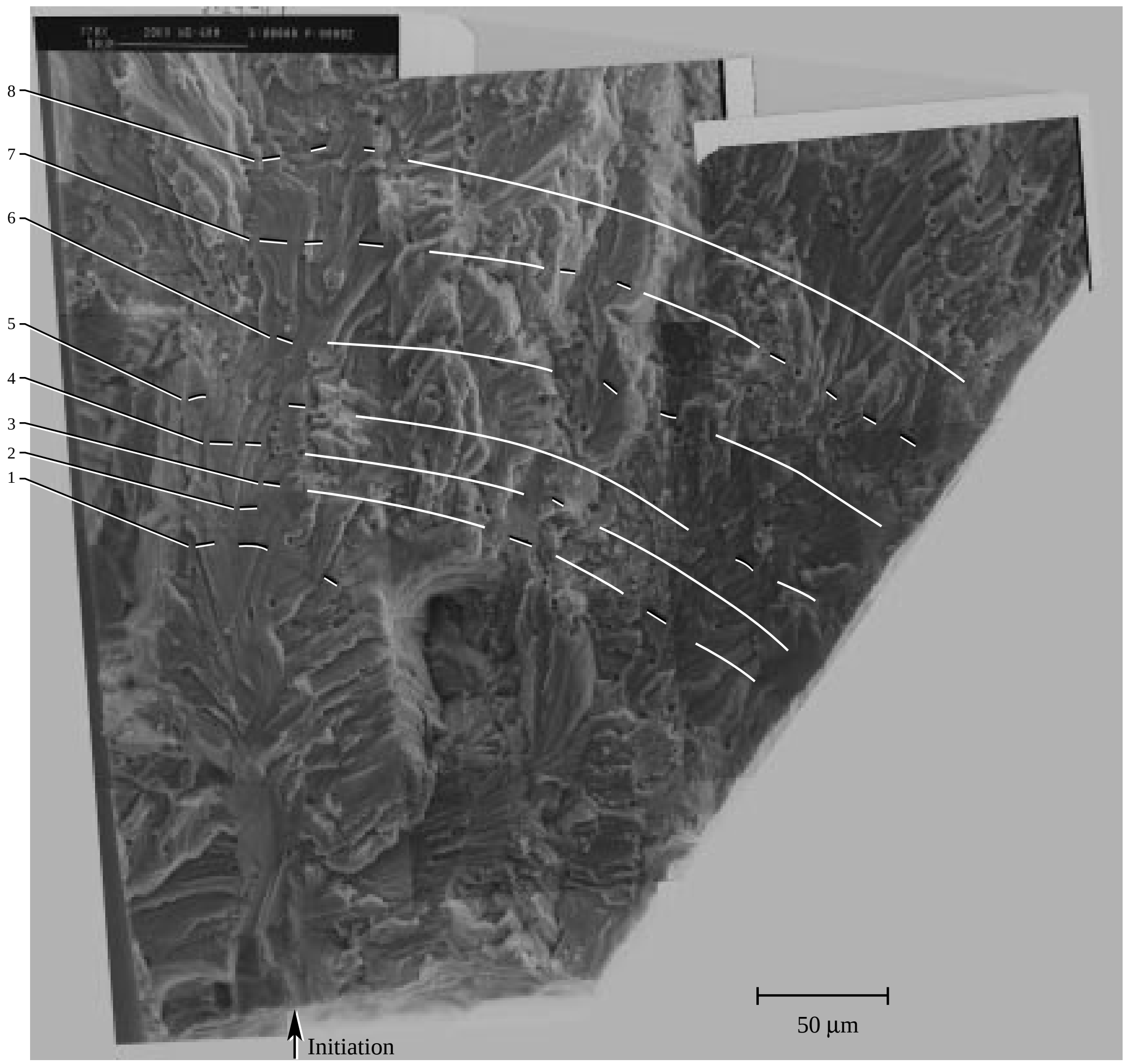


Figure 6a Micrograph montage showing marker band sets and crack fronts for Specimen #2. Marker bands #1-8 are numbered.

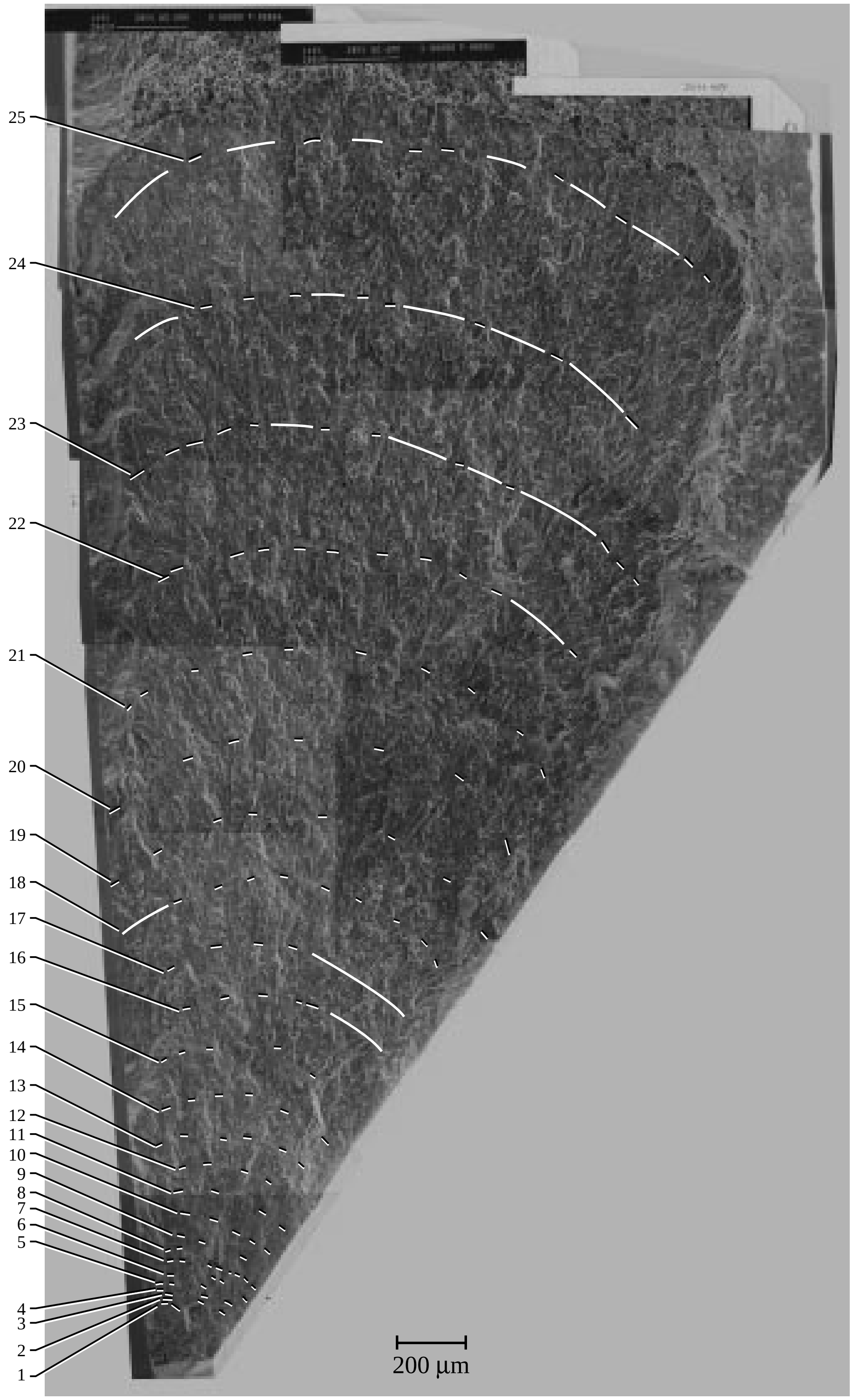


Figure 6b Micrograph montage showing marker band sets and crack fronts near the initiation region of Specimen #2. Marker bands #1-25 are numbered.

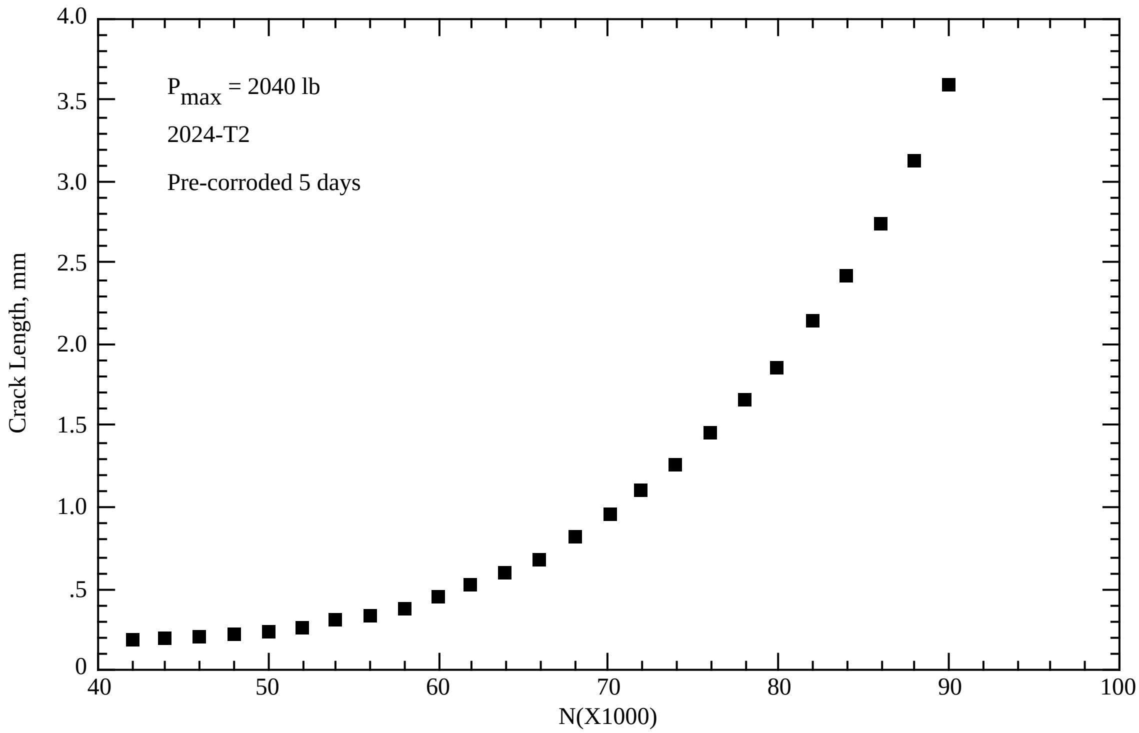


Figure 7 Fatigue crack length vs. cycle count for Specimen #2.

Appendix 1

Appendix 1 contains the coordinates for all of the marker bands from Specimen #1.

Marker Band Number	X Coordinate (mm)	Y Coordinate (mm)
1	0.090	0.050
2	0.110	0.055
3	0.130	0.135
	0.125	0.055
4	0.160	0.110
	0.155	0.145
	0.155	0.040
5	0.175	0.140
	0.155	0.210
	0.180	0.110
	0.170	0.055
	0.165	0.030
6	0.210	0.120
	0.210	0.085
	0.200	0.050
	0.195	0.180
7	0.245	0.130
	0.215	0.045
	0.240	0.085
	0.210	0.200
9	0.320	0.150
	0.310	0.070
	0.300	0.050
	0.300	0.210
8	0.290	0.140
	0.265	0.060
	0.260	0.210
10	0.360	0.210
	0.360	0.100
	0.330	0.270
11	0.440	0.250
	0.355	0.400
	0.450	0.150
12	0.510	0.280
	0.475	0.340
	0.515	0.120

Marker Band Number	X Coordinate (mm)	Y Coordinate (mm)
13	0.580	0.290
	0.530	0.415
	0.460	0.500
14	0.670	0.340
	0.620	0.450
	0.660	0.250
15	0.785	0.370
	0.710	0.520
	0.600	0.625
16	0.910	0.420
	0.845	0.590
	0.740	0.700
	0.900	0.340
	0.890	0.240
17	1.080	0.480
	1.010	0.660
	0.890	0.810
	1.070	0.340
	1.045	0.210
18	1.250	0.610
	1.190	0.795
	1.100	0.990
	1.270	0.350
	1.250	0.260
19	1.515	0.745
	1.390	0.950
	1.320	1.040
	1.460	0.250
20	1.770	0.860
	1.550	1.185
	1.810	0.580
	1.780	0.310
21	2.100	0.970
	1.970	1.260
	2.160	0.670
	1.830	1.380

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13. ABSTRACT (Maximum 200 words)

Groups of striations called marker bands generated on a fatigue fracture surface can be used to mark the position of an advancing fatigue crack at known intervals. A technique has been developed that uses the distance between multiple sets of marker bands to obtain a vs. N, crack front shape, and fatigue crack growth rate data for small cracks. This technique is particularily useful for specimens that require crack length measurements during testing that cannot be obtained because corrosion obscures the surface of the specimen. It is also useful for specimens with unusual or non-symmetric shapes where it is difficult to obtain accurate crack lengths using traditional methods such as compliance or electric potential difference in the early stages of testing.

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